

INTERSTELLAR ORGANIC MATERIAL: COMPARISONS WITH LABORATORY AND SOLAR SYSTEM SPECTRA

Yvonne J. Pendleton
NASA Ames Research Center
Moffett Field, CA 94035

Abstract

Spectra of objects that lie along several lines of sight through the diffuse interstellar medium (DISM) reveal an absorption feature near 3.4 μm , which has been attributed to saturated aliphatic hydrocarbons on interstellar grains. The similarity of the absorption bands near 3.4 μm (2950 cm^{-1}) along different lines of sight indicates that the carrier of this band lies in the diffuse dust. Several materials have been proposed as "fits" to the 3.4 μm feature over the years. A comparison of these identifications is presented. These comparisons illustrate the need for high resolution, high signal-to-noise observational data as a means of distinguishing among laboratory organics as matches to the interstellar material. Although any material containing hydrocarbons will produce features in the 3.4 μm region, the proposed "matches" to the DISM do differ in detail. These differences may help in the analyses of the chemical composition and physical processes that led to the production of the DISM organics. A remarkable similarity between the spectrum of the diffuse dust and an organic extract from the Murchison meteorite suggests that some of the interstellar organic material may be preserved in primitive Solar System bodies. This feature has recently been detected in other galaxies (Bridger et al. 1993, Pendleton 1995, Wright et al. 1996) indicating the widespread availability of organic material for incorporation into planetary systems.

INTRODUCTION

Infrared spectral studies provide insight into the chemical identity of the organic component of the interstellar medium because the fundamental vibrational frequencies of the common chemical bonds between the most chemically abundant elements occur in the mid-infrared ($5000\text{--}400\text{ cm}^{-1}$, $2\text{--}25\text{ }\mu\text{m}$). Infrared spectroscopic techniques have been used to detect organic material in the interstellar medium (Wickramasinghe and Allen 1980, Butchart et al. 1986, Adamson et al. 1990, Sandford et al. 1991, Pendleton 1993, Pendleton et al. 1994) as well as in primitive Solar System bodies such as comets, meteorites, and asteroids (Cruikshank and Brown 1987, Cronin and Pizzarello 1990, Tokunaga and Brooke 1990, Brooke et al. 1991, Ehrenfreund et al. 1991, Mueller et al. 1992, Pendleton and Cruikshank 1994).

Unequivocal identification of the specific molecules responsible for absorption and/or emission features observed in the ISM has met with limited success, in part due to technical constraints on the quality and completeness of astronomical spectra. Until fairly recently, adequate wavelength coverage at sufficiently high resolution and good signal-to-noise ratios were not available to distinguish among several possible "fits" to the $3.4\text{ }\mu\text{m}$ feature. Consequently, the existing data through the C-H region were "fit" with a variety of organic material, including plausible materials such as organic grain mantles (Greenberg 1982, Schutte and Greenberg 1988) and hydrogenated amorphous carbon (HAC) (Jones et al. 1987), and less plausible materials such as *Escherichia coli* bacteria (Hoyle and Wickramasinghe 1962, Hoyle et al. 1982).

Over the years the instrumentation has improved dramatically, so that we are now able to see structure previously hidden in the $3.4\text{ }\mu\text{m}$ region. The $3.4\text{ }\mu\text{m}$ absorption band is actually composed of several bands that correspond to the stretching modes of C-H in saturated aliphatic hydrocarbons (Sandford et al. 1991; Pendleton 1993, 1994; Pendleton et al. 1994; Sandford et al. 1995). In this paper, several comparisons are made of the diffuse dust line of sight toward galactic center IRS 6E and laboratory materials. The astronomical data were obtained at the NASA Infrared Telescope on Mauna Kea using a 32 channel near-infrared grating spectrometer.

DISCUSSION

Several materials have been suggested as candidate carriers of interstellar carbon. These include HAC (cf. Ogmen and Duley 1988, Adamson et al. 1990), quenched carbonaceous composite (QCC)

(cf. Sakata et al. 1987), biological materials (cf. Hoyle et al. 1982), and residues produced by the irradiation of ices (cf. Allamandola et al. 1988, Schutte 1988, Sandford et al. 1991).

HAC can be produced in the laboratory using one of two standard methods: (1) through inefficient hydrocarbon burning in air and (2) by striking an arc in a controlled Ar atmosphere between two amorphous carbon electrodes (cf. Borghesi et al. 1987, Ogmen and Duley 1988). QCC is synthesized from hydrocarbon—principally methane—plasmas (Sakata and Wada 1989). Figure 1a compares the astronomical spectrum of the line of sight toward galactic center source GC IRS 6E with the laboratory spectrum of an HAC sample taken from Borghesi et al. (1987). Figure 1b contains a similar comparison for QCC that has been heated to 450°C. The QCC spectrum was taken from Sakata and Wada (1989). A comparison of GC IRS 6E spectrum to that of QCC at room temperature (not shown) showed that the better match occurred with the heated QCC shown here. Since heating at these temperatures tends to aromatize the mixture, the better match between the heated QCC and the DISM is consistent with our conclusion that the DISM dust contains carbonaceous material other than aliphatics (Sandford et al. 1991, Pendleton et al. 1994). It is clear that both HAC and QCC provide a rough match to the interstellar C–H stretching feature, but that both materials produce a feature that differs from the interstellar feature in some details. It is not surprising that both HAC and QCC fit the interstellar data to first order since both materials contain the $-\text{CH}_3$ and $-\text{CH}_2-$ functional groups thought to be responsible for the interstellar absorption feature. The detailed mismatches in the positions and relative strengths of the various subfeatures are largely a reflection of differences in the relative abundances of $-\text{CH}_3$, $-\text{CH}_2-$, and other chemical groups in the various materials. For example, the weakness of the subfeature near 2960 cm^{-1} relative to the subfeature near 2925 cm^{-1} in the spectra of HAC and QCC when compared with the same bands in the interstellar feature suggests that the interstellar carrier is richer in $-\text{CH}_3$ groups than the particular laboratory samples of HAC and QCC shown here. Other materials (not shown here) that provide equally good comparisons with the interstellar data are the ice tholins (Khare et al. 1993) and ion-bombarded methane (Strazzulla et al. 1995).

Hoyle et al. (1982) have suggested that the C–H stretching band of diffuse dust may be due to organic materials of biological origin. In particular, they claimed that the spectrum of *E. coli* provided a good match to the interstellar C–H stretching feature. While we consider such an identification extremely unlikely, for completeness we have included a comparison of the spectrum of an *E. coli* sample and the spectrum of GC IRS 6E (Fig. 1c). Our spectrum

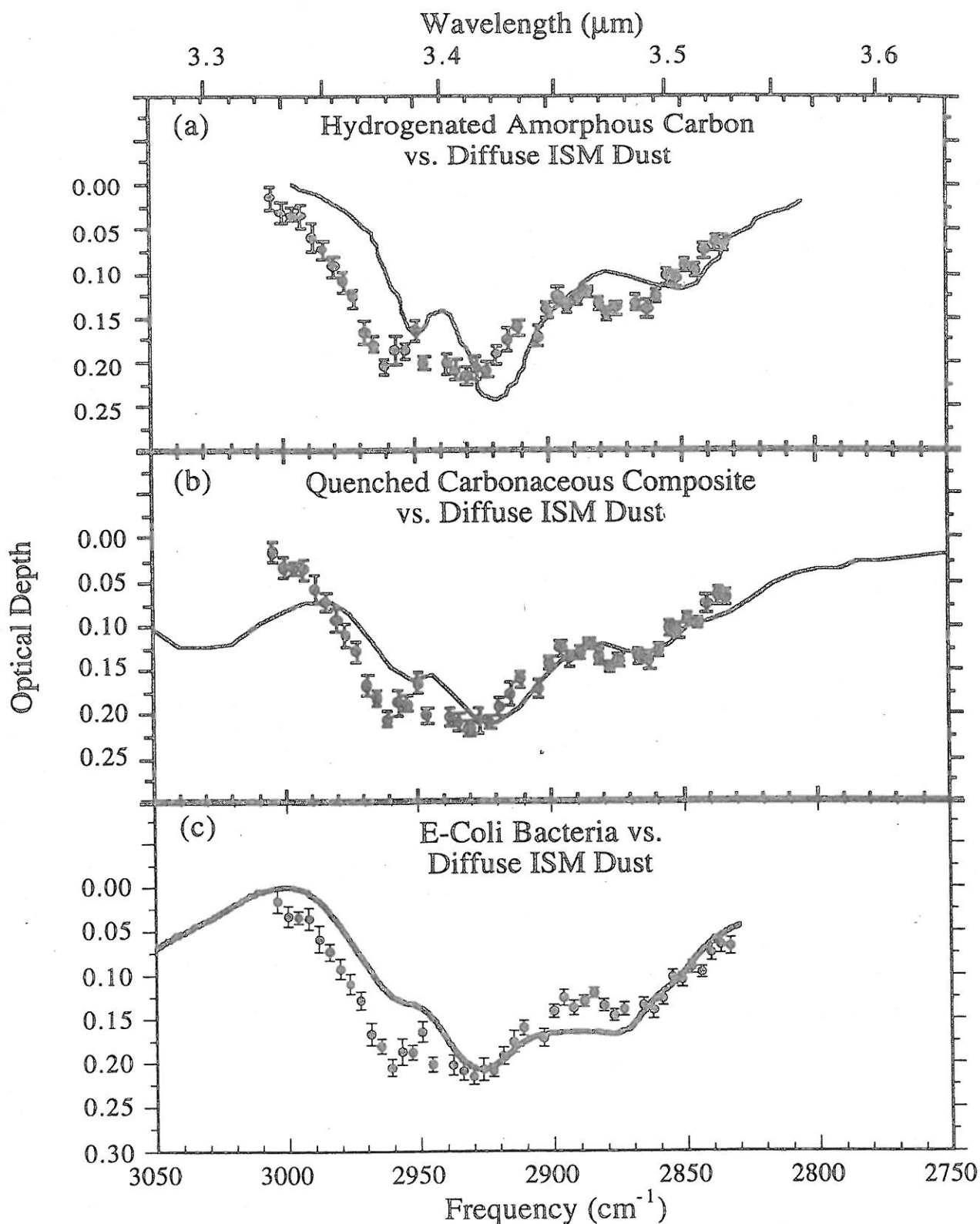


FIG. 1. A comparison of the optical depth spectrum of galactic center source IRS 6E (solid points) with (a) the optical depth spectrum of a room temperature hydrogenated amorphous carbon (HAC) taken from Borghesi et al. (1987; solid line), (b) the optical depth spectrum of a room temperature filmy quenched carbonaceous composite (QCC) taken from Sakata and Wada (1989; solid line), and (c) the optical depth spectrum of *E. coli* suspended in a KBr pellet (solid line).

of *E. coli* was taken at a resolution of one cm^{-1} using a Nicolet 740 Fourier transform infrared spectrometer. The *E. coli* sample was prepared using a standard KBr pellet technique (see Sandford 1984 for a detailed discussion of the sample preparation technique used). As with the spectra of HAC and QCC, the spectrum of *E. coli* is generally similar to the interstellar feature, just as would be expected for any material containing abundant aliphatic $-\text{CH}_3$ and $-\text{CH}_2-$ groups, but differs in detail.

It has previously been shown that the diffuse medium C-H stretching feature is very similar to that produced by residues formed by the UV irradiation and subsequent warming of interstellar ice analogs (Sandford et al. 1991). Infrared spectra of mixed molecular interstellar ice analogs containing H_2O , CH_3OH , CO , and NH_3 reproduce many of the major spectral features attributed to ice in dense clouds (cf. Tielens and Allamandola 1987, Allamandola and Sandford 1988, Allamandola et al. 1988). Ultraviolet photolysis of ices made up of these molecules produces new, more complex compounds. Warming to 150 K leads to the evaporation of the original volatile components of the ices while leaving the more complex C-rich residues behind (see Allamandola et al. 1988 and Bernstein et al. 1994a and b for more detailed discussions of the properties of the laboratory photolysis residues produced from CH_3OH -containing ices). Such a process (photolysis followed by warm-up) is similar to what is thought to occur to ices in dense molecular clouds that are subsequently dispersed into the diffuse medium by star formation and other dynamic processes.

Figure 2a shows a comparison of the spectrum of GC IRS 6E and the spectrum of a residue produced by the UV photolysis and subsequent warm-up to 200 K of an $\text{H}_2\text{O}:\text{CH}_3\text{OH}:\text{NH}_3:\text{CO} = 10:5:1:1$ ice. The quality of the "fit" provided by this laboratory residue is similar to that of the materials discussed earlier; that is, the overall residue feature is similar to the interstellar feature, but differs from it in detail. As with the earlier materials, we note that the lack of a stronger subfeature near 2955 cm^{-1} indicates that the abundance of $-\text{CH}_3$ groups in the laboratory residue is lower than in the carrier of the interstellar feature. This conclusion is supported by Figure 2b, where we show a comparison of the GC IRS 6E spectrum and that of a laboratory residue produced by the UV photolysis and warm-up of an $\text{H}_2\text{O}:\text{CH}_3\text{OH}:\text{NH}_3:\text{CO}:\text{C}_3\text{H}_8 = 10:5:1:1:1$ ice—an ice enriched in $-\text{CH}_3$ groups relative to the one shown in Figure 2a. The resulting laboratory spectrum provides an improved fit to the diffuse medium C-H stretching feature which results from the enhancement in the relative $-\text{CH}_3$ abundance.

Some of the hydrocarbon components in primitive meteorites show strong deuterium enrichments and other isotopic

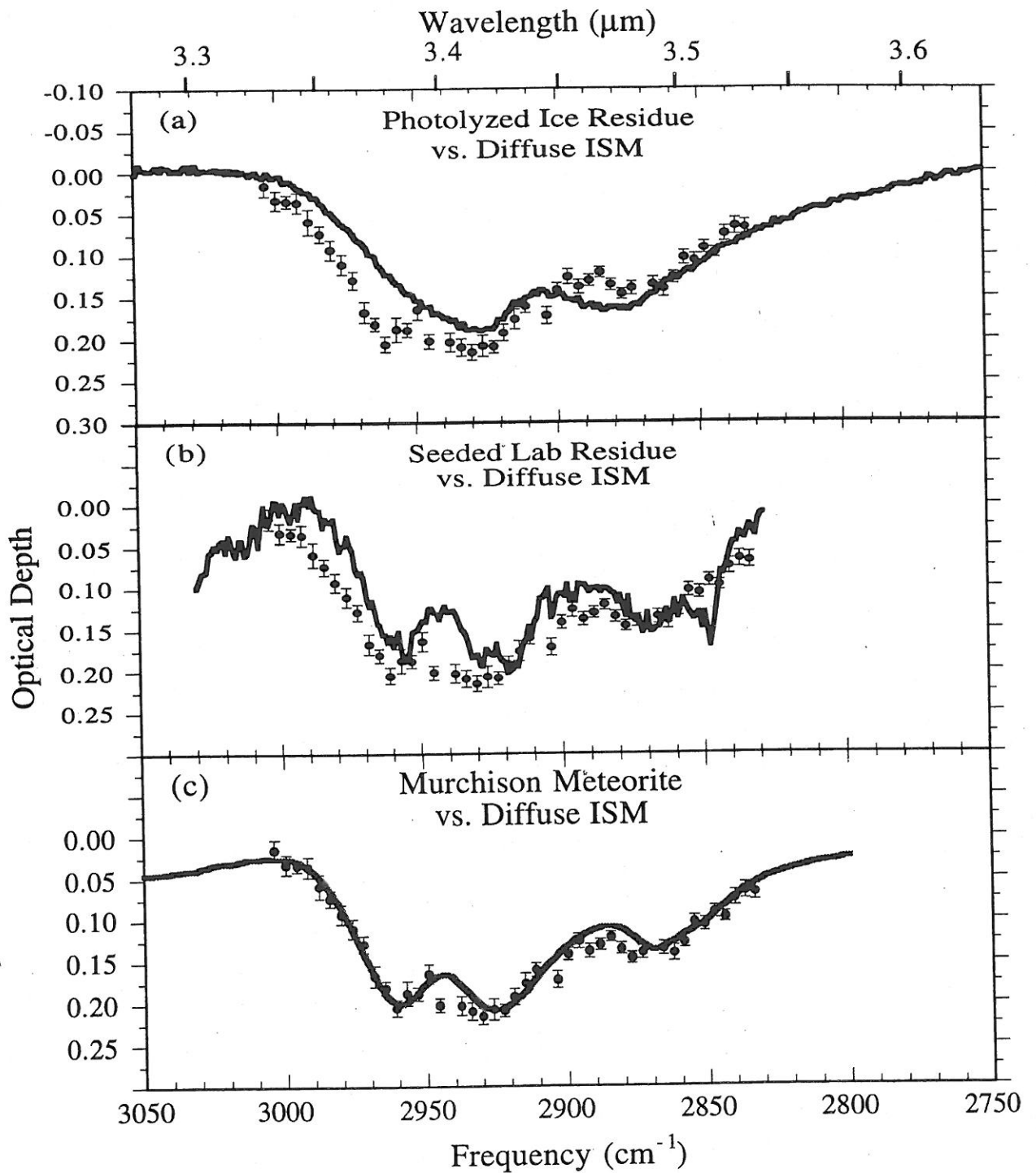


FIG. 2. A comparison of the optical depth spectrum of galactic center source IRS 6E (solid points) with (a) the spectrum of a laboratory residue produced by the UV irradiation of a 10 K $\text{H}_2\text{O}:\text{CH}_3\text{OH}:\text{NH}_3:\text{CO} = 10:5:1:1$ interstellar ice analog followed by warm-up to 200 K (solid line), (b) the spectrum of a laboratory residue produced by the UV irradiation of a 10 K $\text{H}_2\text{O}:\text{CH}_3\text{OH}:\text{NH}_3:\text{CO}:\text{C}_3\text{H}_8 = 10:5:1:1:1$ interstellar ice analog followed by warm-up to 200 K (solid line), and (c) the spectrum of an organic extract from the Murchison meteorite (solid line). The photolysis residue spectra in (a) and (b) were taken from Allamandola et al. (1988) and the meteoritic spectrum was taken from De Vries et al. (1993) and was kindly provided by W. Golden.

anomalies, which indicate a connection to interstellar grains and molecules (Kerridge et al. 1987, Ming and Anders 1988, De Vries et al. 1993, Amari et al. 1994, Lewis et al. 1994). The presence of isotopically anomalous diamonds, SiC, TiC, and graphite in meteorites confirms that some interstellar materials were incorporated into meteorites and survived subsequent processing on the meteorite parent bodies (cf. Anders and Zinner 1993). If the same were true for the organic component of interstellar dust, then the carbonaceous materials observed in the DISM may be one of the "parent" components from which the carbonaceous material in meteorites was derived.

Earlier comparisons of the spectra of the organic extract of the primitive CM meteorite Murchison with the interstellar C-H stretching feature demonstrated a strong similarity (Ehrenfreund et al. 1991). This comparison was made prior to the availability of the high resolution, high signal-to-noise spectra of the diffuse ISM. Figure 2c shows a comparison of the spectrum of GC IRS 6E and the spectrum of a carbonaceous component of the Murchison chondrite taken by De Vries et al. (1993). It is obvious from Figure 2c that the two spectra are remarkably similar in peak positions, widths, and profiles.

It should be noted that another interesting comparison with the carbonaceous component of the Murchison meteorite has recently been made by Lee and Wdowiak (1993) who have obtained the spectrum of a residue produced by passing a discharge through a gaseous mixture of hydrogen and the simplest polycyclic aromatic hydrocarbon, naphthalene ($C_{10}H_8$). In general, the spectrum of their residue provides a good overall match to the meteoritic data throughout the midinfrared region but, like all the other laboratory materials discussed above, their residue appears to have a higher ratio of $-CH_2-$ to $-CH_3$ groups than the carrier of the interstellar band. Therefore, while the spectral fit of their residue to the meteoritic data is quite impressive and provides additional support for the idea that the interstellar carrier may contain aromatic materials, it does not provide as compelling a match to the interstellar C-H stretching feature as does the meteoritic material itself.

Several points can be made from the comparisons shown in Figures 1 and 2. First, as has long been known, it is clear that virtually any material that contains substantial amounts of aliphatic $-CH_3$ and $-CH_2-$ groups will produce a feature whose overall position and profile is similar to that of the diffuse interstellar C-H stretching feature. Thus, the general fits provided by all the spectra in Figures 1 and 2 support the idea that dust in the diffuse medium contains abundant aliphatic $-CH_3$ and $-CH_2-$ groups. In this regard, it is unlikely that spectral comparisons of the astro-

thanks goes to Rose Grymes and Linda Jahnke in the Life Sciences Division at NASA Ames for providing the laboratory samples of *E. coli*, to Scott Sandford for the spectral analyses of those samples, to G. Strazzulla for data in advance of publication, and to A. Sakata for the QCC data. This work was partially supported by NASA grants 185-52-12-09 and 199-52-12-04 (Exobiology), 188-44-21-04 (Astrophysics), and 452-33-93-03 (Origins of Solar Systems).

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